Smoke Ventilation of Common Access Areas of Flats and Maisonettes (BD2410) - Final Factual Report
Appendix C (CFD modelling)

The authors of this report are employed by BRE. The work reported herein was carried out under a Contract placed by the ODPM. Any views expressed are not necessarily those of the ODPM.

Introduction and general discussion

The numerical simulations reported in this appendix were undertaken in parallel to the review (Appendix A) and the reduced-scale physical modelling study (Appendix B), to provide complimentary information for the purpose of providing recommendation for the revision of Approved Document B. A wide range of scenarios have been modelled, examining a range of natural and mechanical smoke management schemes, from 'simple' vents in external walls to corridor smoke extraction systems and stair pressurisation methods.

Appendices D to F summarise the full set of simulations. Steady-state analyses were undertaken here, representing conditions that may be expected after some five to ten minutes if the fire size, geometric conditions and smoke ventilation settings were to remain fixed in time. A limited number of time-dependent simulations were undertaken, which confirmed that the steady-state analyses were representative of conditions after this interval of time. The most important results parameters, illustrated in Appendices D to F, are the 'visibility distance' contours and the gas temperatures, which together provide a means for assessing the distribution of smoke and thermal hazard. Of particular interest here are the conditions inside the corridor / lobby, and whether smoke enters the adjoining stair.

It should be stressed that the results of the numerical simulations were intended to provide a measure of the relative performance of the different smoke management schemes studied, and NOT an actual prediction of conditions in any 'real life' situation. For this reason the approach adopted was to consider a ventilated, but smoke filled, fire compartment adjoining a corridor / lobby, in turn adjoining a stair, through fixed vertical 'door openings'. For the majority of simulations a door gap of 0.1m wide (by 2m high) was assumed, which provided a suitable 'smokey conditions' scenario against which to compare the smoke control performance of the various measures. While, in the pre-firefighting stage such conditions can be considered as particularly severe (given that the fire doors should provide significantly better protection), they do provide a good baseline against which to measure relative performance. Doorway openings up to 0.78 m were considered when addressing the firefighting stage, where open (or partly open) doorways could be expected.

It should be stressed that, for drawing recommendations for Approved Document B, the results from the numerical simulations provided information additional to that from the review and the physical modelling, and that overall conclusions have not been drawn from any one element of the project alone.

CFD fire modelling

General information on CFD

Numerical fire models based on the methods of computational fluid dynamics (CFD) provide detailed predictions of the distribution of the flow patterns, temperatures, smoke species etc associated with a fire.

CFD models take as their staring point the system of coupled partial differential equations that describe the conservation of mass, momentum, energy and chemical species. These equations, known as the Navier-Stokes equations (momentum and mass conservation) and the related general advection-diffusion transport equation (energy and species conservation), describe both laminar and turbulent fluid flow. A solution, in time and space, is obtained by integrating and discretising the equation set over a spatial and temporal grid, and then solving the resultant set of algebraic equations by an appropriate numerical method. This yields a discrete set of solution values for velocity, temperature etc at each spatial grid point (each one corresponding to one control volume) at each time step.

However, to resolve precisely the turbulent structures characteristic of fire induced flow would require spatial and temporal grids far to fine for practical solution. Thus is due to the small time and length-scales of the smallest turbulent eddies. An approximate form of the conservation equations must therefore be solved, and the influence of turbulence incorporated in some appropriate manner. There are two main approaches available:

- Large eddy simulation (LES). This is the more 'fundamental' approach. Here the larger time- and length-scales are modelled explicitly, i.e. the larger turbulent eddies are predicted directly from the solved equation set. The effect of the smaller eddies is then incorporated via an additional subgrid scale sub-model, which approximates the so-called subgrid scale Reynolds stress that 'appears' as a result of the eddy filtering operation.

- Solution of the Reynolds-averaged Navier-Stokes (RANS) equations. This is the approach adopted in most CFD models for practical engineering applications. Here, rather than solve for the 'true' unsteady, turbulent fluctuating variables, the underlying equations are expressed in a form where the dependent variables are written as a sum of a time-averaged component and a fluctuating component, where the latter represents the effect of turbulence. Unfortunately, this renders the set of differential equations more complicated, with the introduction of extra terms referred to as the Reynolds stresses and the turbulent scalar fluxes. These terms have to be solved for, or modelled in some manner, in addition to the time-averaged components.

  Rather than solve the Reynolds stresses and the turbulent scalar fluxes individually, the eddy-viscosity approach involves the solution of only two extra equations. These two-equation models generally solve for turbulent kinetic energy (κ) and the dissipation rate of κ (ε), to defines an 'eddy-viscosity' that models the effect of turbulence on the flow field as an increased viscosity, i.e. a enhanced viscosity consisting of the addition of a 'turbulent viscosity' to the 'true' laminar viscosity.

Steady-state and time-varying RANS solutions can be obtained. Here it is important to note while a time-varying solution yields the evolution of the time-averaged variables, the time-dependent turbulence information is lost as a consequence of the averaging process.

Other than the treatment of turbulence, the main feature that differentiates general CFD models from each other is the numerical mesh (grid) that is constructed to solve the system of equations. Fire specific CFD models are further characterised by the sub-modelling approach adopted for the treatment of the physical processes of combustion, radiation, boundary heat transfer etc. Information on the above is provided, for example, in [Versteeg and Malalasekera, 1995] and [Cox, 1995].

The BRE JASMINE model

The BRE model JASMINE was selected for the CFD simulations in this project.

JASMINE has been developed continuously over 20 years at BRE, during which time it has been validated against a range of fire experiments, e.g. [Cox et. al., 1986], [Miles, 2001] and [Miles et. al., 2000]. It has been applied to numerous smoke movement and fire development applications within buildings, tunnels and transport vehicles. An example of a building application is provided by the previous project on smoke ventilation of fire fighting shafts [Harrison & Miles, 2002], which included validation against a selection of the fire experiments performed in the 1/5-th scale rig.

JASMINE solves the Reynolds-Averaged Navier Stokes (RANS) equations of fluid flow on a single-block Cartesian grid, generating a solution value for velocity, temperature, smoke concentration etc at each grid location. JASMINE uses the finite volume method, where the differential equations are first transformed into an integral form and then discretised on the control volumes (or cells) defined by the numerical grid. This solution procedure is coupled with a variant of the SIMPLE pressure-correction scheme.

A standard κ-ε model with additional buoyancy source terms incorporates the effect of turbulence [Markatos et. al., 1982], and standard wall functions for enthalpy and momentum describe the turbulent boundary layer adjacent to solid surfaces. Transient solutions are generated by a first-order, fully-implicit scheme.

Combustion was modelled using an eddy break-up model [Magnussen & Hjertager, 1976] in which the fuel pyrolysis rate is specified as a boundary condition. Fuel consumption is then calculated at all control volumes as a function of fuel concentration, oxygen concentration and the local turbulent time-scale (provided by the κ-ε model). A simple one-step, infinitely fast chemical reaction is assumed, with complete oxidation of the fuel assumed when sufficient oxygen is available. The eddy break-up model is appropriate for turbulent diffusion flames characteristic of fire, where the rate of reaction is controlled by the comparatively slow mixing of fuel with oxygen.

'Visibility distance' can be calculated as a function of combustion products (generally CO_2) or by using an empirical relationship relating visibility to the local concentration of obscuring particles (soot) [Jin, 1978]. The concentration of obscuring particles is generally solved for by assuming a fixed yield at the fire source, i.e. a fixed fraction of the pyrolysed fuel is assumed to be (soot) particles that are transported as a conserved scalar.

Radiant heat transfer was modelled in this study with the six-flux model [Gosman & Lockwood, 1973]. Local absorption-emission properties were computed using Truelove's mixed grey-gas model [Truelove, 1976], which calculates the local absorption coefficient as a function of temperature and gas species concentrations.

While the focus of the work in this project was on steady state analyses, selected transient simulations were performed (using the same time-independent boundary conditions) for visualisation purposes and to confirm that the steady state solutions were representative of conditions that would be found after the order of ten minutes of a transient analysis.

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Geometric scenarios investigated

A set of three generic geometries was selected for the main body of the CFD analysis reported in this appendix. These were developed, and agreed, during the initial part of the project and at the first two meetings of the Steering Group [Miles, 2003 & 2004b], and later extended to include larger fire sizes [Miles, 2004e]. Figures C1, C2 and C3 illustrate, in plan view, the three geometries, which in summary are:

– Geometry 1 - a fire compartment opening onto a lobby, which in turn opened onto a stair.

  The common lobby, with cross-sectional plan dimensions 2.5 m by 5 m, separated the dwelling (fire compartment) from a common stair. Smoke and make-up air ventilation were provided at one or both ends of the lobby, indicated LEFT and RIGHT in Figure C1.

– Geometry 2 - a fire compartment opening onto a corridor, which in turn opens onto a lobby and then a stair.

  This was a more complex geometry, with the fire compartment opening onto a common corridor (1.5 m by 18 m), which in turn opened onto a common lobby (2.5 m by 5 m). The common stair was then on the other side of this lobby. Ventilation measures were applied only at the lobby in this geometry (indicated LEFT and RIGHT in Figure C2), so that the corridor could was an unventilated, internal section of corridor, protected by a fire door at each end.

– Geometry 3 - a fire compartment opening onto a corridor, which in turn opens onto a stair.

  This was as for the lobby scenario above, except that the common corridor had cross-sectional plan dimensions 1.5 m by 18 m and the common stair was at the far end of the corridor with respect to the fire compartment. Again, smoke and make-up air ventilation was provided at one or both ends of the corridor, indicated LEFT and RIGHT in Figure C3, and additionally (in some scenarios) at the mid-point of the corridor (indicated as CENTRE in Figure C3).

Figure C4 illustrates the CFD geometry and mesh for one of the scenarios for geometry 2, showing the fire compartment, corridor and a smoke shaft at one end of the corridor.

Whereas in the initial work [Miles, 2004c & 2004d] the stair was not included in the simulations, it has been included in all the final simulations (reported here). This has allowed the overall degree of protection to be assessed, in terms of both the corridor/lobby and the stair. A judgement on the relative performance of different smoke management schemes can then be made, e.g. good protection of the stair at the possible expense of conditions inside the corridor.

For all geometries, the height of the compartment and lobby/corridor was 2.2 m and the floor-to-floor height 2.5 m. However, a sub-set of Geometry 2 scenarios were simulated with a ‘tall lobby’, i.e. the height of the lobby was extended from 2.2 to 2.5 m.

For the majority of simulations the fire compartment was located on the second storey (i.e. two stories above ground level) of a five storey building. Some simulations were performed with the fire compartment on the second storey of 10 and 20 storey buildings. These were conducted to investigate the performance of natural smoke shafts in taller buildings.

The fire compartment, in all scenarios, was ventilated to the outside through a small low-level opening. This ensured that air was available for combustion, and provided for a completely smoke logged compartment. The arrangement ensured that the majority of the combustion products were then transported from the compartment to the adjoining corridor / lobby, and that air was drawn into the compartment from the outside only, i.e. fresh air was supplied via the small opening to the outside, and the smoke was then transported through the compartment door opening.

A steady fire size of 0.25 MW, combined with the low level rear vent to the outside and a 0.1 m door gap to the adjoining corridor (extending the full height of the 2 m door), was used in the main series of simulations. This combination of fire size, ventilation conditions and compartment size provided a smoke filled compartment and suitable scenarios against which to compare the performance of different smoke management schemes when exposed to a smoke filled dwelling to which the door has not closed properly. A series of simulations were also undertaken with larger fire sizes of 1 and 2.5 MW, with the compartment door opened to 0.5 m and 0.78 m respectively, to allow conditions of greater thermal load, possibly encountered during firefighting operations, to be addressed.

Table C1 summarises the three fire compartment conditions used in the scenarios reported here, together with the approximate temperature and mass and heat transfer rates passing through the door gap / opening into the adjoining corridor / lobby. The values in the table were those generated in the simulation of geometry 3 (lobby and corridor) with two 1 m^2 external wall vents in the lobby and a top and bottom vent to the stair (and the corridor unventilated). Note that the exact temperature and heat / mass transfer rate depended on the actual scenario (smoke management scheme), as this influenced to some degree the amount of smoke drawn into the corridor / lobby. However, the variation in the door gap / opening smoke 'source' was relatively small for the majority of the smoke management schemes (the main exception being some of the pressurisation examples where air was forced from the corridor into the fire compartment).

In the main series of simulations the 'opening' between the lobby / corridor and the stair, and in the third geometry between the internal corridor and the lobby, was also a 0.1 m gap running the full height of the door (2 m). The purpose of the simulations was simply to compare the relative performance of the various schemes, and not to represent a general 'real-life' situation, where in practice conditions may be less severe (because the doors should be expected to function better, and steady-state conditions will generally represent a worst-case situation). Doors opened to 0.5 m and 0.78 m, mimicking possible conditions during fire-fighting operations, were also investigated in some scenarios.

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Table C1 Summary of performance of schemes for lobby geometry

FIRE SIZE (MW)	EXTERNAL WALL VENT SIZE (M^2)	DOOR GAP WIDTH (M) (X 2M HIGH)	MEAN TEMPERATURE OF SMOKE PASSING THROUGH DOOR GAP (°C) *	MASS FLOW RATE OF SMOKE THROUGH DOOR GAP ($KG\ S^{-1}$)	HEAT FLOW RATE THROUGH DOOR GAP (KW)
0.25	0.65	0.1	210 (160-270)	0.2	40 kW
1	0.95	0.5	350 (180-450)	0.9	350 kW
2.5	1.9	0.78	690 (530-910)	1.4	1.1 MW

* The values in brackets are the lower and upper bounds

It is important to note that in Table C1 the discrepancy between the heat convected through the door gap / opening and that generated by the combustion process is due to the boundary heat losses within the fire compartment (see below). For the type of scenarios considered, these losses can be expected to be high, as is reflected in Table C1.

Convection and radiation heat losses to the solid boundaries were included within the fire compartment, lobby/corridor and also the smoke shafts. A surface temperature calculation was included within the fire compartment, i.e. the temperature of the CFD surface cells at the fire compartment walls etc were calculated according to an assumed thermal penetration during a 'quasi-steady' time interval of ten minutes. The other surfaces, however, were considered as being isothermal (at ambient temperature), which means that the heating of these surfaces was not calculated. This will have 'maximised' the boundary heat losses at these surfaces, and can be considered a conservative assumption in that it will have tended to reduce the effect of any stratification inside the lobby / corridor and also the efficiency of the naturally ventilated smoke shafts.

'Visibility distance' was calculated from the local concentration of obscuring particles (soot). The concentration of obscuring particles was computed approximately by assuming a fixed yield at the fire source, i.e. a fixed fraction of the pyrolysed fuel was assumed to be (soot) particles that are transported as a conserved scalar. In this study a 10% yield of particulates at the fire source has been assumed. An empirical correlation for light-reflecting signs [Jin, 1978 & 2000] was employed in estimating the 'visibility distances'. It should be noted that such visibility calculations are indicative only, and were used to compare the conditions using the alternative corridor smoke management measures rather than to derive quantitative values. Furthermore, the assumed yield of particulates will have arguably resulted in conservative 'visibility distances', i.e. on the low (smokey) side.

Wind and stack effects have been included in a number of simulations by imposing a relative static pressure outside the appropriate vent of opening.

Figure C5 illustrates a typical numerical grid employed in the study. In the corridor, lobby, etc the typical maximum cell dimension was 0.2 m. This was reduced at critical locations such as the 0.1 m wide door gaps, where the grid size was reduced to 0.025 m. Larger cell dimensions were allowed at other locations, in particular in the vertical direction away from the fire floor where values up to approximately 0.5 m were allowed. Figure C6 shows examples of the vector plots generated.

Smoke ventilation schemes investigated

The following smoke ventilation schemes, and combinations of, have been investigated in the CFD simulations:

- External wall vents of cross-sectional area 0.5 m^2, 1 m^2 and 1.5 m^2, located either at high or low level.
- Naturally ventilated smoke shafts of cross-sectional area 0.25 m^2, 0.5 m^2, 0.75m^2, 1 m^2, 1.5 m^2 and 3 m^2, with either open or closed bases. In the results presented, a single smoke shaft was considered, located either at one end of the corridor / lobby or (in the corridor geometries) at the centre, with the vent into the shaft located on the end / side wall. Various size of ventilation openings (from the lobby / corridor into the shaft) have been investigated
- Mechanically powered extraction from the corridor / lobby, with the vent into the exhaust shaft located as for the naturally ventilated smoke shafts (i.e. at one end of the corridor / lobby or (in the corridor geometries) at the centre, with the vent into the shaft located on the end / side wall).
- Mechanically powered smoke exhaust ventilation from the ceiling of the corridor, balanced with floor level makeup air. For the corridor there were three ceiling exhaust vents, while for the (shorter) lobby there were two only.
- Pressurised stairwells, with air supply at top of the stair and an opening of 1 m^2 at the base of the stair. This simple arrangement was chosen for numerical convenience to allow comparison of its performance and the required (mechanical) effort against that of the alternative natural and mechanical measures, and does not represent a particular proposed pressurisation method.

Figure C7 illustrates a combination of a smoke shaft at one end of the lobby and a low level make-up air vent at the other. With respect to the provision of make-up air vents, these could in practice either be located directly on an external wall or could be provided via a shaft or duct to the outside.

CFD simulations performed

A total of over 500 steady-state CFD simulations have been conducted, examining the various combinations of geometric scenario, fire size and smoke ventilation scheme.

Appendices D to F summarise the result of each simulation, and allow the relative conditions inside the corridor / lobby and stair to be compared. It should be noted that each CFD simulation contains a lot more information than shown in the appendices. However, for the purpose of comparing the hazard conditions for each scenario the succinct representation of the results in the appendices is considered appropriate.

Table C2 summarises the sets of scenarios modelled, one in each appendix.

Table C2 Summary of scenarios modelled

APPENDIX	GEOMETRY	FIRE SOURCE (AND DOOR GAP TO DWELLING)	DOOR OPENING TO STAIR (M) *
Di	Dwelling, lobby & stair	0.25 MW (0.1 m door gap)	0.1
Dii	Dwelling, lobby & stair	0.25 MW (0.1 m door gap)	0.78
Diii	Dwelling, lobby & stair	1 MW (0.5 m door gap)	0.5
Div	Dwelling, lobby & stair	2.5 MW (0.78 m door gap)	0.78
Ei	Dwelling, corridor, lobby & stair	0.25 MW (0.1 m door gap)	0.1
Eii	Dwelling, corridor, lobby & stair	0.25 MW (0.1 m door gap)	0.78
Eiii	Dwelling, corridor, lobby & stair	1 MW (0.1 m door gap)	0.5
Eiv	Dwelling, corridor, lobby & stair	2.5 MW (0.78 m door gap)	0.78
Ev	Dwelling, corridor, 'tall-lobby' & stair	0.25 MW (0.1 m door gap)	0.1
Fi	Dwelling, corridor & stair	0.25 MW (0.1 m door gap)	0.1
Fii	Dwelling, corridor & stair	1 MW (0.5 m door gap)	0.5
Fiii	Dwelling, corridor & stair	2.5 MW (0.78 m door gap)	0.78

* Also door opening between corridor and lobby where present

For each simulation in the Appendices D to F the following information is provided:

- A summary of the smoke management provision in terms of the corridor / lobby vent method (natural or mechanical). Here L, R and C denote the left, right and centre location within the corridor / lobby as indicated in Figures C1, C2 and C3. SD refers top the door to the stair (where in some mechanical scenarios a ventilation path was provided in addition to the door gap / opening). Where the stair is vented (top and/or bottom) this refers to a vent to the outside with an area approximately 1 m^2.

  Details of the smoke shaft cross-sectional area, vent area etc is provided as appropriate.

  Additional information is provided where appropriate regarding on an external static pressure at an external opening (to mimic the effect of adverse wind or building stack pressure).

  Where mechanical exhaust or supply is included, this is defined in terms of the air change per hour in the corridor / lobby (mechanical extraction) or the stair (air supply for pressurisation). The corresponding volumetric flow rate is given also.

- 'Visibility distance' contours in an elevation(s) containing the corridor / lobby (but not the unventilated corridor section in the second geometric scenario (corridor, lobby and stair) and the stair. The contour range is such that the colour red represents a calculated 'visibility distance' of 1 m or less. Note that this should be interpreted as being 'very smokey' rather than representing a precise distance. Recall also the comments that the steady-state scenarios with fixed door gaps / openings were designed to provide a relative measure of the performance of alternative smoke management schemes under onerous conditions and NOT to generate predictions for any particular real-life scenarios.

  Where there is no smoke in the stair, i.e. the 'visibility distance' is everywhere > 7 m (and generally significantly higher than this), then a note to this effect is provided.

- The mean (volume weighted) gas temperature in the lower 1.5 m zone of the corridor / lobby (the lobby in the case of the second geometric scenario with the unventilated corridor separating the compartment and the lobby).

- In a number of the mechanically ventilated scenarios the equivalent 'cold flow' design pressure differential and open door air speed is provided. These values were provided by non-fire simulations where:

  - A 'closed door pressure differential' was measured across the closed stair door with the mechanical system running at the defined rate (ach or volumetric flow rate). The door to the fire compartment was closed also, but all other vents (including the stair vent(s)) were open.

– An average ‘open door velocity’ was measured across the fully open stair door (0.78 m opening width) with the mechanical system running at the defined rate. The door to the fire compartment was again closed, and all other vents (including the stair vent(s)) were open.

The purpose of these ‘cold flow’ simulations was to examine whether mechanical systems could be specified sensibly in terms of a design closed door pressure differential (with the stair side at the higher pressure) and, if required, an open door average air speed (from the stair into the adjoining corridor / lobby). In particular, one aim of this analysis was to see whether the CFD simulations would indicate design pressure differentials and open door air speed compatible with those in existing guidance [e.g. British Standards Institution, 1998].

It should be noted, however, any such values derived from the ‘cold-flow’ CFD simulations are NOT directly translatable to design criteria suitable for publications such as Approved Document B, but instead require interpretation in the light of issues such as the actual closed/open door arrangements to be considered and the allowance required for adverse wind and stack pressures etc.

Figures C8 to C10 indicate the location of the elevations where the ‘visibility distance’ contours are shown in Appendices D to F.

Summary of findings from the CFD analysis

For each group of scenarios (appendix) the findings are summarised below, where in all cases with a 0.25 MW fire the door gap to the dwelling is 0.1 m (and 0.5 m and 0.78 m for the 1 MW and 2.5 MW fires respectively). Only a brief summary is given, and for the 'complete picture' Appendices D to F should be consulted. Furthermore, in the summary of Appendix Dii onwards only findings additional to those already presented are described.

Appendix Di (lobby & stair geometry, 0.25 MW fire, 0.1 m door gap to stair)

- <u>No vents to lobby.</u>

  As expected, heavily smoke logged conditions were generated inside the lobby. The stair in these examples (top and bottom vented stair) was also smoke logged from the fire storey to the top.

- <u>External wall vents to lobby.</u>

  In the absence of any adverse wind or stack pressure, the provision for two external vents, one on either side of the lobby, offered reasonably good protection to the stair. Furthermore, conditions inside the lobby were greatly improved compared to no vents, with good stratification of smoke. There was only minor difference in the performance of 1.5 m^2 and 1 m^2 vents.

  The level of protection to the stair was reduced where only one side of the lobby was vented. However, in the absence of adverse wind/stack pressures the conditions inside the lobby were comparable to those where two sides of the lobby were vented. The size of wall vent, and whether it was 'split' between an upper and lower section, had only a modest effect.

  The effect of modest (2 Pa) wind/stack induced static pressures was quite noted in the examples examined, causing conditions inside the lobby to deteriorate with a reduction in smoke stratification. With respect to conditions in the stair, a negative pressure at the lobby vent helped to protect the stair, while a positive pressure resulted in more smoke in the stair.

- <u>Naturally ventilated smoke shafts to lobby.</u>

  Closed base smoke shafts ('chimneys') provided effective protection to the stair provided the stair was vented. Where the top of the stair was vented (1 m^2 in the scenarios modelled), and in the absence of adverse wind / stack pressures, smoke shafts from 0.25 m^2 to 3 m^2 in cross-section were fully effective in protecting the stair. Conditions inside the lobby, however, were poorer then those obtained, in general, with external wall vents.

  Increasing the distance from the fire storey to the top of the shaft (buildings up to 20 stories were investigated) had no detrimental effect on the performance of the smoke shaft.

Good resilience to adverse wind / stack pressures was shown with a 1 m^2 cross-section shaft, where positive static pressures up to 5 Pa (at the head of the shaft) did not prevent the smoke shaft from protecting the stair. Note, however, results in Appendix Ei with the additional corridor (and where the smoke in the lobby was then cooler), which demonstrated that adverse wind / stack pressures can effect the performance of naturally vented smoke shafts.

Where there was no vent from the stair to the outside, the operation of the smoke shaft in protecting the stir was compromised. This prevented the natural depressurisation of the lobby relative to the stair and the associated flow of fresh air from the stair to the lobby. With only a single (1 m^2) vent from the stair to the outside, then locating this vent at the top of the stair was (in the absence of adverse wind/stack effects) better than at the base of the stair. However, the provision of a vent either at the top or base of the stair was of primary importance, and the location of secondary.

The details of the vent from the lobby into the smoke shaft, i.e. area and location, were not critical in the scenarios covered by Appendix Di.

Providing a low level makeup air vent at the opposite end of the lobby helped conditions inside the lobby by providing some smoke stratification. There was some limited evidence, however, that the level of protection to the stair may then be slightly reduced.

While open-base smoke shafts improved conditions marginally inside the lobby (but not to the level achieved by having a makeup air vent or to the level achieved by external wall vents), the protection to the stair was compromised in, with some smoke entering the stair in two of the examples (where it had not done so in the equivalent closed-base cases).

– Mechanical extraction into shaft at side of lobby.

By extracting at a suitably high level it was found for this geometry, and shafts sizes investigated, that it was possible to protect the stair from smoke while also providing a moderate degree of stratification of smoke inside the lobby. If the extraction rate was it sufficiently high, then smoke was able to enter the stair. This approach can be considered as a mechanical depressurisation one, where the lobby is maintained at a lower pressure than the adjoining stair.

As for the naturally ventilated smoke shafts, the provision of a vent from the stair to the outside was required in order for the stair to be protected from the ingress of smoke (where the mechanical extraction rate from the lobby was sufficiently high).

For the scenarios modelled here, replacement fresh air was allowed to enter the lobby either from a dedicated makeup air vent, or in a few of the scenarios from e vent to the stair. The provision for makeup air to a mechanical extraction system is important.

A mechanical extraction rate of approximately 160 lobby air changes per hour (ach^{-1}) was required in order to protect the stair (there was some dependence on the extract shaft size and makeup air vent size), which equated to 1.2 m^3s^{-1}. As reported above, equivalent 'closed stair door' pressure differentials and 'open stair door' average air speeds were calculated by performing the appropriate pre-fire (cold flow) CFD simulations. For the combinations of exhaust shaft cross-section and makeup air vent size, the 160 ach^{-1} extraction rate corresponded to a closed door pressure differential of between 2 and 6 Pa and an open door average air speed of about 0.5 ms^{-1}, which are comfortable within the requirements specified in the British Standard [British Standards Institution, 1998]. However, when making comparisons it should be noted that the design conditions in the British Standard do not correspond directly with those used in this study, and that the design criteria actually set will take into account compensatory performance for wind / stack pressures etc.

Note furthermore that the mechanical depressurisation method described here is not actually covered by [British Standards Institution, 1998]. It is, in effect, the reverse of a pressurised lobby (with no pressurisation of the stair or dwellings), which is not excluded from the Standard.

– Mechanical extraction at ceiling of lobby.

  At a sufficiently high extraction rate (again about 160 lobby ach^{-1}), this proved to be an effective method to provide both good conditions inside the lobby (by virtue of keeping the smoke at ceiling level) and to protect the stair. It should be noted, however, that the effects of adverse pressures and the influence of opening/closing doors on the stratification of the smoke has not been investigated. Furthermore, the practical matter of providing suitable ceiling extraction points and floor / low level replacement air supplies should be borne in mind.

– Pressurisation of stair.

  The numerical investigation into pressurisation of the stair by means of 'simple' top supply and ground level air relief indicated that the stair could be protected from ingress of smoke for the scenarios of Appendix Di by a combination of a sufficient air supply rate and the provision of air / smoke relief in the lobby.

  Where this air / smoke relief was at floor level inside the lobby the required air supply rate in the star was 40 stair ach^{-1}, equating to 1.6 m^3s^{-1}. And where the air / smoke relief was at ceiling level the required air supply rate was reduced to about 20 stair ach^{-1}, equating to 0.8 m^3s^{-1}. Conditions inside the lobby, however, remained smoke filled. The corresponding cold flow design conditions were then between about 2 and 6 Pa for the closed stair door pressure differential, and between about 0.2 and 0.4 ms^{-1} for the open stair door average air speed. These values are comparable to those for the mechanical depressurisation of the lobby reported above. Again, the issue of the actual design arrangements and the account of adverse wind / stack pressures should be noted.

  The final plots in Appendix Di illustrate that by extending the pressurised space to the lobby, by removing the air / smoke relief (and venting to the outside only from the fire compartment), it is possible to protect also the lobby. However, protection to the dwellings was not considered in any depth, and these simulations should be taken as 'approximate illustrations'.

Appendix Dii (lobby & stair geometry, 0.25 MW fire, 0.78 m door gap to stair)

Here, with the open door to the stair, external wall vents (on one side of the lobby) offered little protection to the stair.

Closed-base natural smoke shafts were, however, still effective in protecting the stair for in the case of 0.75 m^2 and 1 m^2 shafts (the sizes investigated), in the absence of adverse wind / stack pressures. However, simulations with the opening at the top of the shaft reduced by 50% indicated that the performance of the smoke shaft could be compromised by this arrangement.

In the case of mechanical extraction from the lobby (depressurisation), it was now necessary to increase the extraction rate to 320 lobby ach^{-1} to protect the stair. The corresponding cold flow closed stair door pressure differential was now 25 Pa and the open stair door average air speed 1 ms^{-1}. By increasing the extraction rate to 640 lobby ach^{-1} good conditions were obtained inside the lobby. The corresponding cold flow design parameters were a closed stair door pressure differential of 92 Pa and an open stair door average air speed of 2.1 ms^{-1}.

For stair pressurisation with ceiling level air / smoke relief from the lobby the required air supply rate was 40 stair ach^{-1}, for which the cold flow design parameters were a closed stair door pressure differential of 6 Pa and an open stair door average air speed of 0.4 ms^{-1}.

Appendix Diii (lobby & stair geometry, 1 MW fire, 0.5 m door gap to stair)

For these scenarios with a larger fire and a 0.5 m door opening to the stair (representative of conditions that may be more likely in a firefighting stage), external wall vents were unable to protect the stair.

A natural smoke shaft of cross-sectional area 1m^2 was able to protect the stair from smoke ingress. Furthermore, while a 0.75 m^2 shaft did not protect the stair in the baseline scenario of a fire on the second storey of a five storey building, when the number of stories was increased to ten (the fire still on the second storey), the increased stack effect created by the smoke shaft was sufficient to protect the stair from smoke. An indication of the optimum location of the vent from the lobby to the smoke shaft was shown in the simulations with a 1 m^2 smoke shaft, where the stair was kept completely smoke free when the vent was at high level (the top at ceiling level), but not when it was located at a lower level.

Mechanical extraction from the lobby (depressurisation) was able to protect the stair when the extraction rate was increased to 640 lobby ach^{-1}. The corresponding closed stair door pressure differential and open stair door average air speed cold flow conditions were either 92 Pa and 2.1 ms^{-1} respectively or 28 Pa and 1.7 ms^{-1}, depending on the size of replacement air vent used. This latter point emphasises the fact that numerical simulations of generic scenarios such as those in this study provide general findings rather than 'precise' real-life predictions.

Stair pressurisation was examined with low level air /smoke relief from the lobby. Here, an air supply rate of between 80 and 160 stair ach^{-1} was required to protect the stair from smoke. The corresponding closed stair door pressure differential and open stair door average air speed cold flow conditions were between 23 & 90 Pa and 0.8 & 1.6 ms^{-1} respectively.

Appendix Div (lobby & stair geometry, 2.5 MW fire, 0.78 m door gap to stair)

Under these severe conditions, external wall vents were unable to offer any protection to the stair.

Natural smoke shafts of cross-sectional area 1.5 m^2 and 2 m^2 were able to protect the stair when the vent to the shaft extended the full height of the lobby. Smaller vents, not extending the full height of the lobby, resulted in some smoke entering the stair.

Protection to the stair was only provided in the mechanical extraction (depressurisation) scenarios when the extraction rate was very high (~ 1000 lobby ach^{-1}).

Pressurisation of the stair achieved protection with an air supply rate of 160 stair ach^{-1}, for which the cold flow design parameters were a closed stair door pressure differential of 90 Pa and an open stair door average air speed of 1.6 ms^{-1}.

Appendices Ei (corridor, lobby & stair geometry, 0.25 MW fire, 0.1 m door gap to stair and between corridor & lobby)

A main difference in the 'corridor, lobby & stair' scenarios is that the smoke in the lobby is cooler than in the lobby & stair scenarios (due to cooling in the unventilated corridor section). They arguably then provided a greater test with respect to adverse wind / stack pressures, for the natural ventilation schemes in particular, as the relative influence of these forces relative be to the buoyancy of the smoke gases was increased.

With external wall vents, conditions inside the lobby were less favourable compared to the 'lobby & stair' scenarios, due to the reduced buoyancy of the smoke and the lower tendency for stratification.

While natural smoke shafts, with shaft cross-sections as low as 0.25 m^2, were still successful in protecting the stair in the absence of adverse wind / stack pressures, simulations indicated that the presence of these effect could prevent the smoke shaft being effective. An adverse pressure of typically 2 Pa could result in smoke entering the stair. While open-base smoke shafts were successful in protecting the stair in the scenarios examined, their performance was not as good as that from closed-base shafts.

As for the 'lobby & stair' scenarios mechanical extraction (depressurisation) could be effective at protecting the stair, but did not provide good conditions inside the lobby for the cases examined. At an extraction rate of 80 lobby ach^{-1} the stair was protected from smoke. The corresponding closed stair door pressure differential and open stair door average air speed cold flow conditions were about 2 Pa and 0.3 ms^{-1}, the exact value depending on the size of replacement air vent used. This approach was reasonably robust with respect to adverse wind / stack pressures acting on the stair openings.

While the ceiling extraction method could again protect the stair, it was not as effective in providing good conditions inside the lobby compared to the corresponding 'lobby & stair' scenarios. This was a consequence of the lower buoyancy of the smoke.

Stair pressurisation was effective in the scenarios investigated with an air supply rate of 10 to 20 stair ach^{-1} (depending on whether low or high level air / smoke relief vents were located in the lobby). The corresponding cold flow design parameters were a closed stair door pressure differential of about 1 Pa and an open stair door average air speed of 0.1 to 0.2 ms^{-1}. Again, the conditions inside the lobby were smoke filled.

Appendix Eii (corridor, lobby & stair geometry, 0.25 MW fire, 0.78 m door gap to stair and between corridor & lobby)

Here a natural smoke shaft of 1 m^2 was fully effective at protecting the stair, while one of 0.75 m^2 allowed only a small amount of smoke into the stair (in the absence of adverse wind / stack pressures).

Mechanical extraction (depressurisation) was effective at protecting the stair when the extraction rate was increased to 320 lobby ach^{-1}, for which the corresponding cold flow design parameters were a closed stair door pressure differential of about 25 Pa and an open stair door average air speed of about 1 ms^{-1}.

Stair pressurisation was not investigated for this arrangement.

Appendix Eiii (corridor, lobby & stair geometry, 1 MW fire, 0.5 m door gap to stair and between corridor & lobby)

The main finding from these (limited) simulations was that a 1m2 natural smoke shaft protected the stair, while a 0.75m^2 shaft allowed some smoke to enter the stair, and a 0.5 m^2 shaft allowed a more significant amount of smoke to enter.

Appendix Eiv (corridor, lobby & stair geometry, 2.5 MW fire, 0.78 m door gap to stair and between corridor & lobby)

Under these severe conditions a 1.5 m^2 natural smoke shaft allowed some smoke into the stair (larger shafts were not investigated).

Mechanical extraction (depressurisation) was effective at protecting the stair when the extraction rate was increased to 640 lobby ach^{-1}, for which the corresponding cold flow design parameters were a closed stair door pressure differential of 92 Pa and an open stair door average air speed of about 2.1 ms^{-1}.

Stair pressurisation was not investigated for this arrangement.

Appendix Ev (corridor, tall-lobby & stair geometry, 0.25 MW fire, 0.1 m door gap to stair and between corridor & lobby)

By increasing the floor to ceiling height of the lobby, the level of protection to the stair offered by external wall vents (in the lobby) was improved. In particular, by locating the external wall vent above the level of the top of the doors, it was possible to stop smoke entering the stair. However, with a modest wind / stack pressure of 1 Pa the benefit was 'lost', with smoke then entering the stair.

Appendices Fi (corridor & stair geometry, 0.25 MW fire, 0.1 m door gap to stair)

Again, a comprehensive set of steady state scenarios were simulated, and only findings adding important additional information to that reported above are outlined here.

As for the corresponding 'lobby & stair' scenarios, although external wall vents did not in general protect the stair from smoke, the situation was significantly improved on that with no ventilation to the corridor. Depending on the vent details, a reasonable degree of stratification could be achieved inside the corridor in some cases. Again, the performance could be influenced by modest wind / stack pressures.

Natural smoke shafts as small as 0.5 m^2 provided protection to the stair, but again adverse wind / stack pressures could compromise their performance. It was observed that the location of the smoke shaft was not significant, i.e. whether it was at one end of the corridor of the other, or at the centre, was not important. As for the other geometries, a natural smoke shaft dir not provide good conditions inside the corridor.

Mechanical extraction (depressurisation) was effective at protecting the stair when the extraction rate was increased to about 80 corridor ach^{-1}, the exact value depending on the arrangement of exhaust shaft and replacement air. The corresponding cold flow design parameters were a closed stair door pressure differential of between 2 and 6 Pa and an open stair door average air speed of about 0.5 ms^{-1}. In general the corridor was quite smoke filled. However, by reducing the extraction rate it was in some cases possible to achieve improved conditions inside the corridor by virtue of a stratified smoke layer, but at the expense of allowing smoke into the stair. At high extraction rates it was possible, in some arrangements, to both protect the stair and provide reasonable or good conditions inside the corridor. This provided, in effect, a mechanical cross corridor smoke clearance scheme. However, the carefully engineered design would be require for such systems since the performance was dependent on the exact geometry and furthermore, the pressure differentials produced may be quite high.

Ceiling level smoke extraction, at the appropriate rate, could be effective at protecting the stair and providing good conditions inside the corridor.

Stair pressurisation was effective in the scenarios investigated with an air supply rate of 20 to 40 stair ach^{-1} (depending on whether low or high level air / smoke relief vents were located in the lobby). The corresponding cold flow design parameters were a closed stair door pressure differential of between 1.5 and 6 Pa and an open stair door average air speed of 0.1 to 0.2 ms^{-1}. The location of the air / smoke relief vents inside the corridor was not important. Again, the conditions inside the lobby were smoke filled.

Appendix Fii (corridor & stair geometry, 1 MW fire, 0.5 m door gap to stair)

External wall vents did not provide protection to the stair.

In the absence of adverse wind / stack pressures, natural smoke shafts down to 0.75 m^2 in cross-section provided protection to the stair (a 0.5 m^2 shaft did not), but did not prevent smoke filled conditions inside the corridor. A reduction in the cross-sectional area of the shaft at the top compromised its performance, the effect being more noted for the smaller shafts.

A limited number of mechanical extraction (depressurisation) scenarios were simulated. For the arrangement investigated, an extraction rate of 320 corridor ach^{-1} was able to protect the stair, for which the corresponding cold flow design parameters were a closed stair door pressure differential of 102 Pa and an open stair door average air speed of 2.2 ms^{-1}. It should be noted, however, the required values may be different for alternative extract duct and replacement air vent configurations.

Appendix Fiii (corridor & stair geometry, 2.5 MW fire, 0.78 m door gap to stair)

For these severe conditions, a 1.5 m^2 natural smoke shaft provided protection to the stair in cases where the vent from the corridor into the stair was at least 1.5 m^2 in area. A 1.25 m^2 shaft allowed some smoke into the stair. As for the smaller fires, the location of the smoke shaft was not important.

As for the scenarios in Appendix Fii, an extraction rate of 320 corridor ach^{-1} was a sufficient for the mechanical extraction (depressurisation) method to protect the stair.

Concluding remarks for the CFD analysis

The findings from the CFD analysis should be interpreted in the light of the scenarios modelled, which themselves were intended to examine the relative performance of alternative smoke management options under 'smokey' conditions rather than provide 'real-life' predictions. They have formed supporting evidence, which together with the review (Appendix A) and the physical modelling study (Appendix B) have allowed recommendations for modifications to Approved Document B to be made. Hence, this and the other appendices should be read as supporting evidence for the recommendations, and not design guidance in themselves.

The most important findings from the CFD simulations are summarised below:

- If exposed to smoke from a dwelling fire for more than a short duration, the adjoining common corridor / lobby can be expected, in general, to become smoke filled. In the absence of appropriate smoke management measures, neighbouring corridors / lobbies and stairwells can also be expected to become smoke filled.

- While external wall vents to the lobby / corridor may in some circumstances maintain tenable conditions inside these spaces (by virtue of creating a stratified smoke layer), in general a specially engineered mechanical solution would be required in order to maintain tenable conditions. This could be in the form of either a smoke extraction scheme or a pressurisation scheme with protection extended into the common corridors.

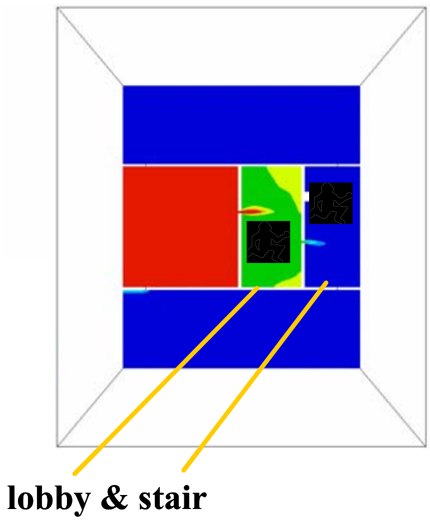
- Protection to a stair adjoining the common lobby / corridor can be more easily achieved.

  Naturally ventilated smoke shafts (in the corridor) can provider an effective means to protect the stair, and in general seem to perform better than external wall vents (in the corridor) in this respect. However, conditions inside the corridor were shown in the simulations to be generally better with the external wall vents. While smoke shafts down to 0.5 m^2 (and sometimes smaller) in cross-section were able to protect the stair in the smaller fire scenarios, where the fire size was larger (and the door openings greater), shaft areas of 1 to 1.5 m^2 were required. Both smoke shafts and external wall vents were in some cases susceptible to adverse wind / stack pressures.

  Mechanical extraction from the corridor (with provision for replacement air) was able to protect the adjoining stair by depressurising the corridor space relative to the stair. As for the natural smoke shafts, conditions inside the corridor remained generally smoke filled.

  Direct pressurisation of the stair was also an effective means to protect the stair. Where air / smoke relief was provided in the corridor fairly modest air supply rates in the stair sufficed in keeping smoke out. Again, conditions inside the corridor generally remained smoke filled.

A series of 'cold flow' (pre-fire) simulations with the stair door in closed and open positions allowed estimates of the required closed stair door pressure differential and open stair door average air speed top be made. In the case of the smaller fire size and door opening scenarios, the corresponding design pressure differentials and open door air speeds were well within the values currently specified for Class A systems in the British Standard [British Standards Institution] (50 Pa and 0.75 ms^{-1}). Where larger fire sizes (and door openings) were considered, the design pressure differentials and open door air speeds were in reasonable agreement with those for Class B systems in the British Standard (50 Pa and 2 ms^{-1}). However, it is important to note that the actual door opening arrangements and vent locations were not the same as in the British Standard, and so the comparison should be considered as illustrative only.



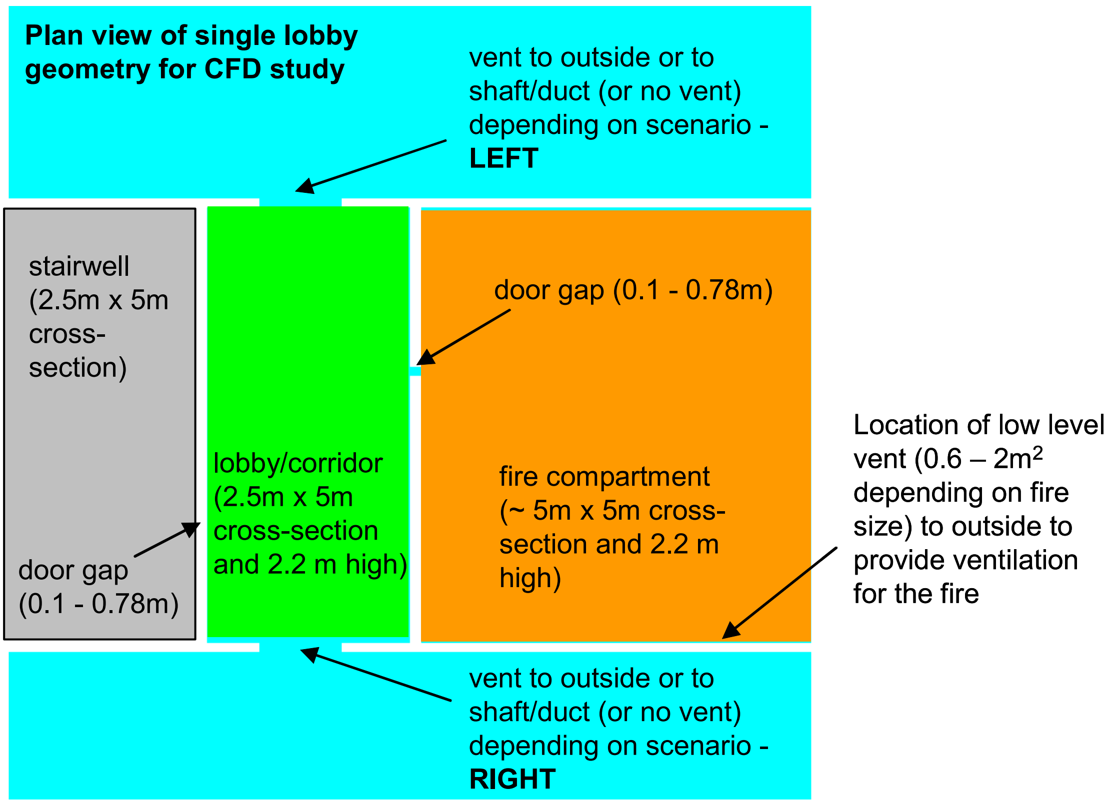


Figure C1 Plan of single lobby geometry for numerical modelling

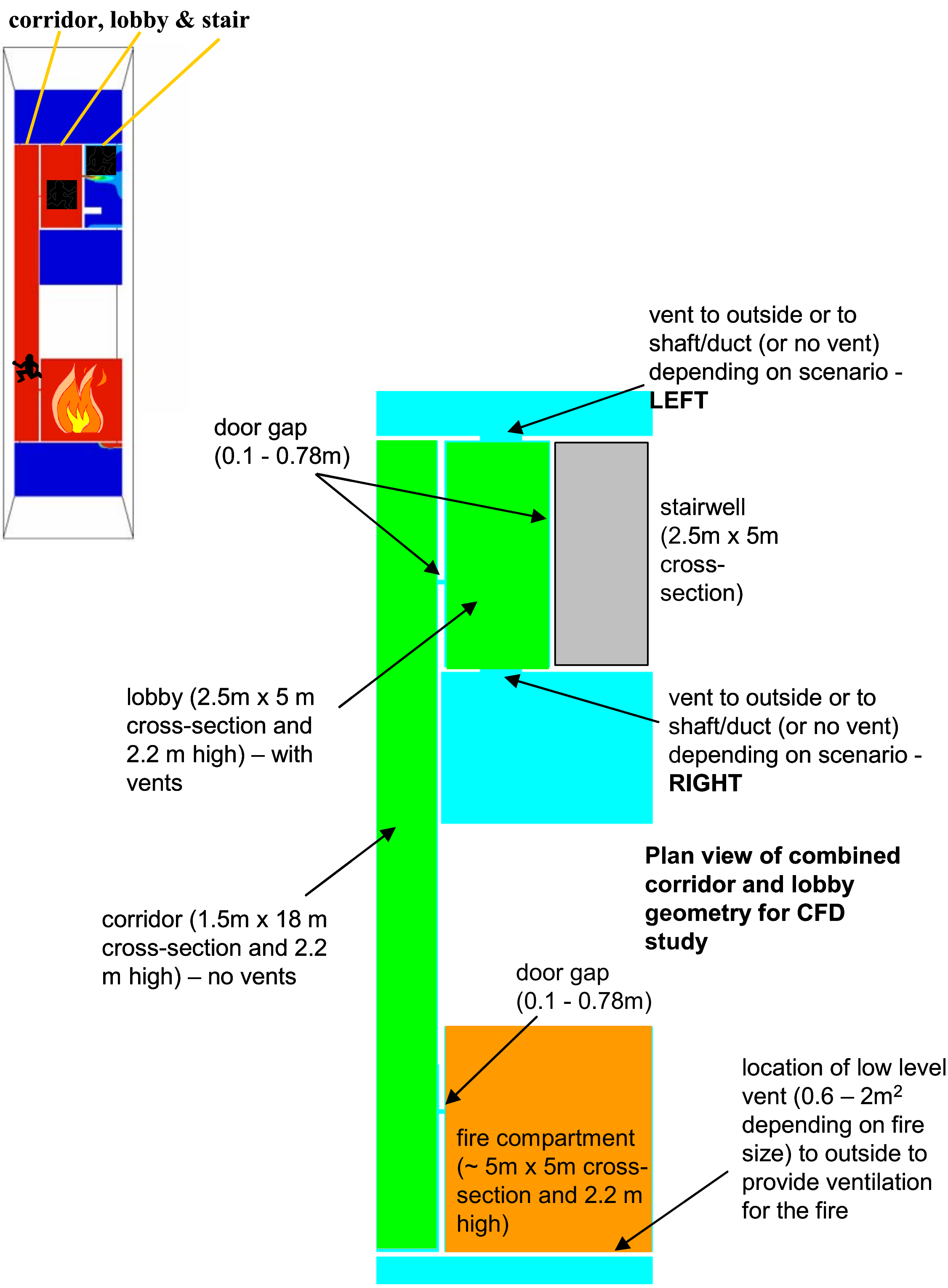


Figure C2 Plan of corridor and lobby geometry for numerical modelling

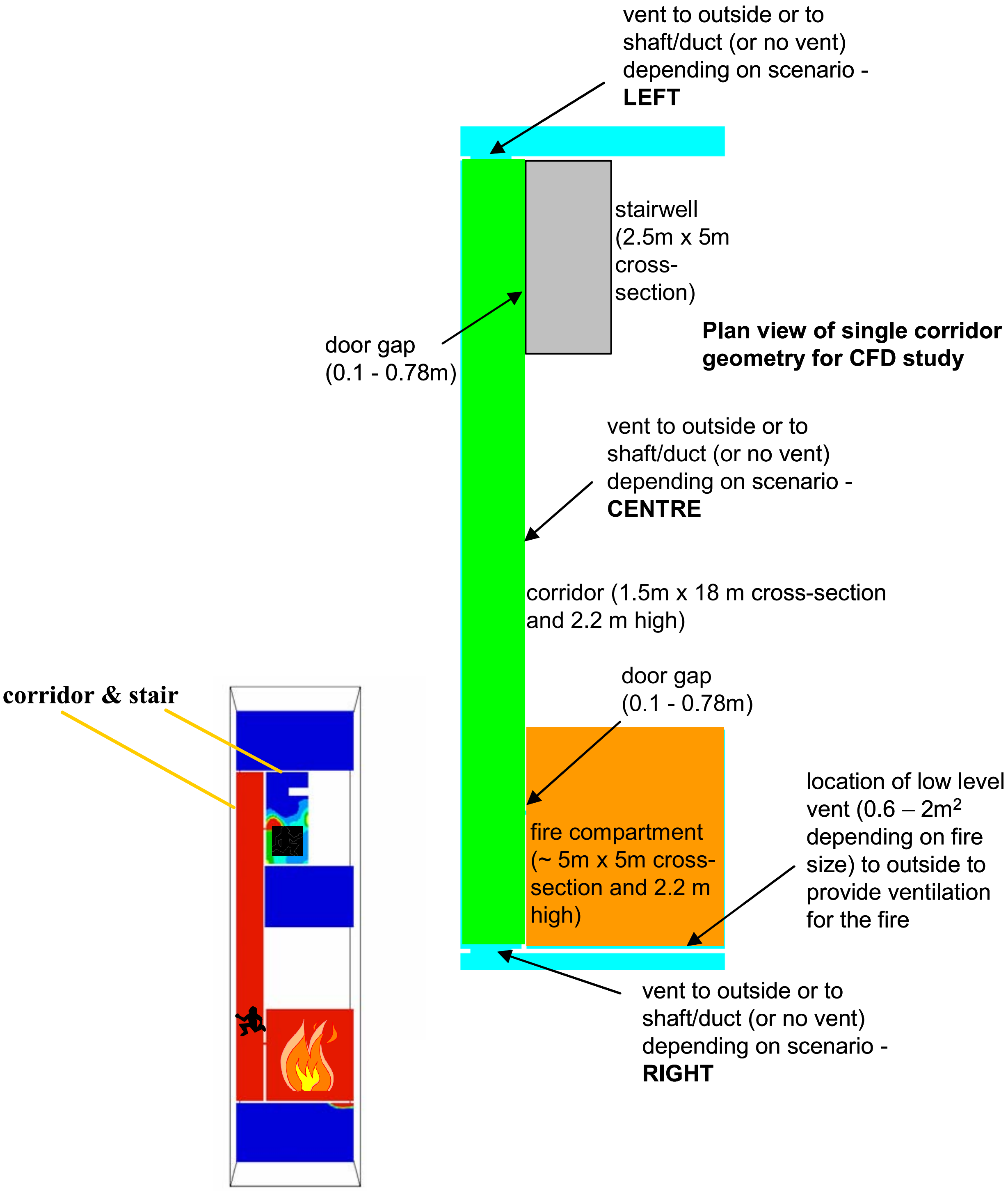


Figure C3 Plan of single corridor geometry for numerical modelling

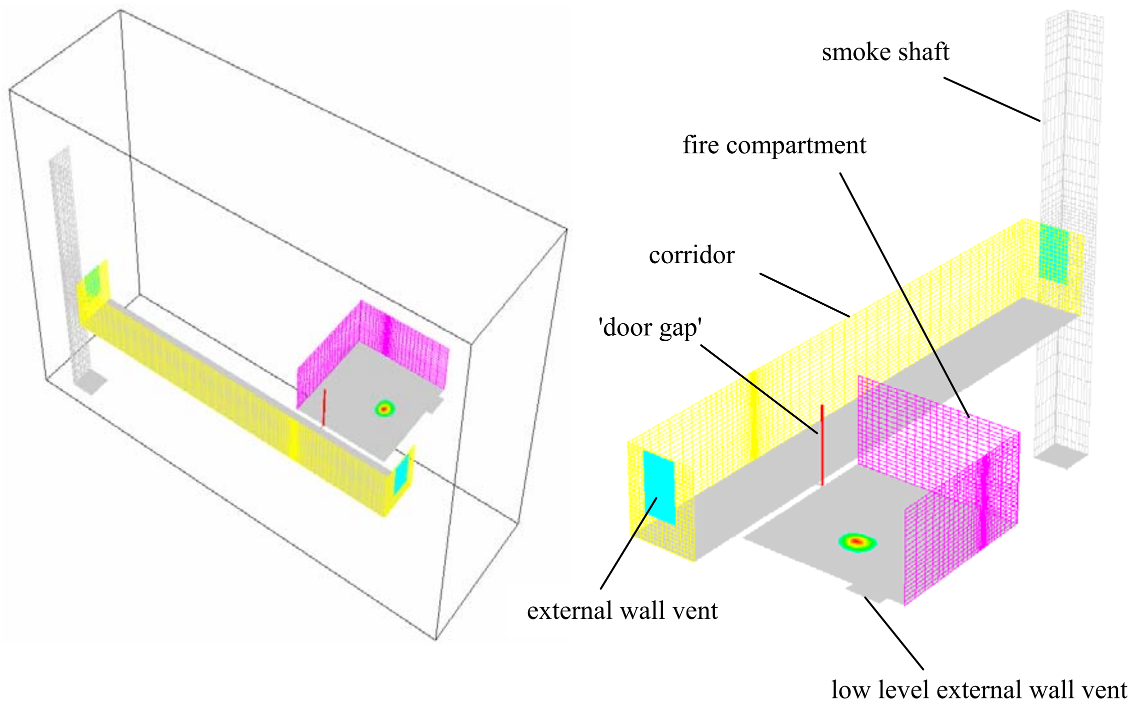


Figure C4 Illustration of CFD geometry showing a fire compartment, corridor, wall vent and smoke shaft

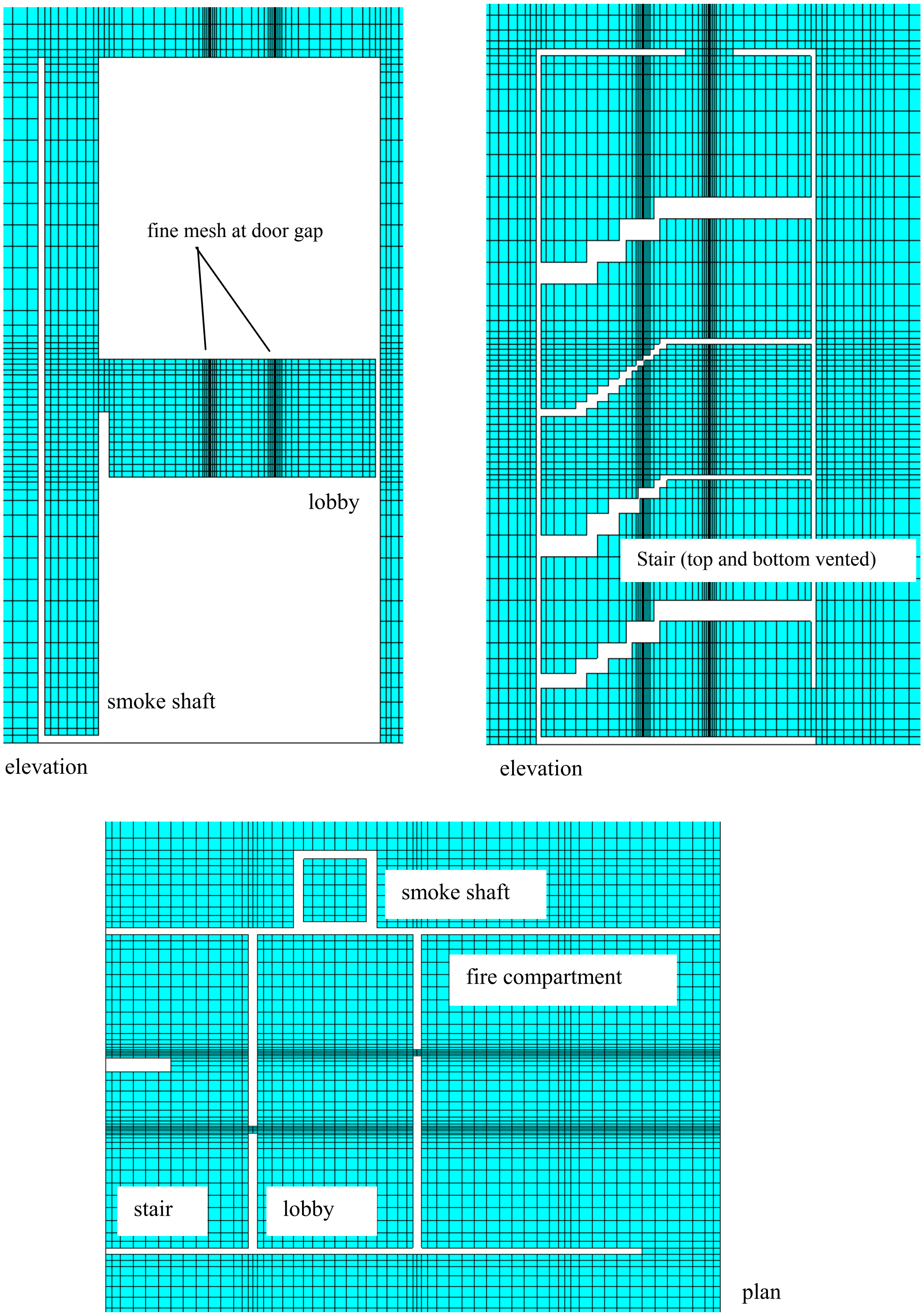


Figure C5 Example CFD mesh for a scenario with a lobby and naturally ventilated smoke shaft

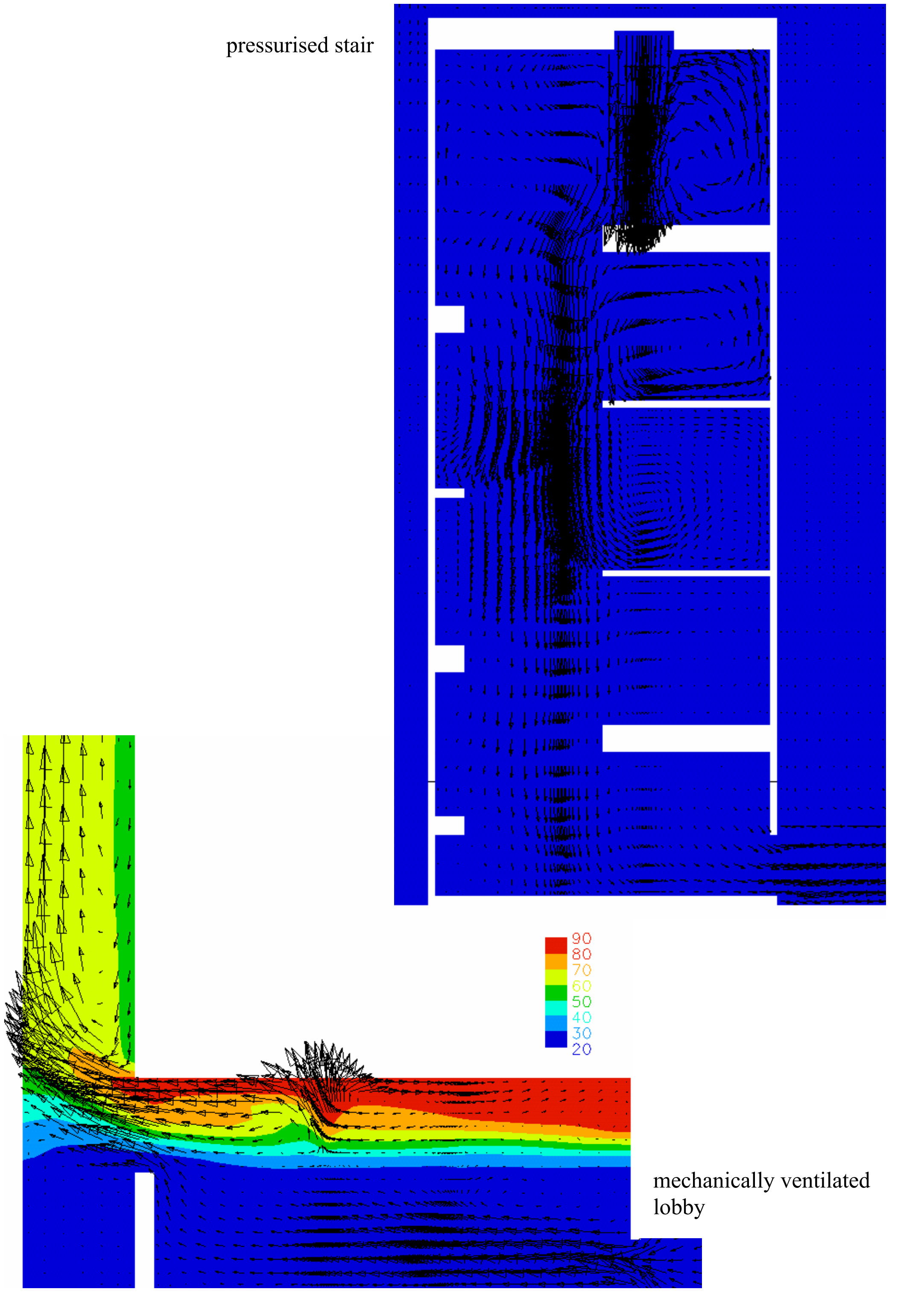


Figure C6 Example CFD vector plots

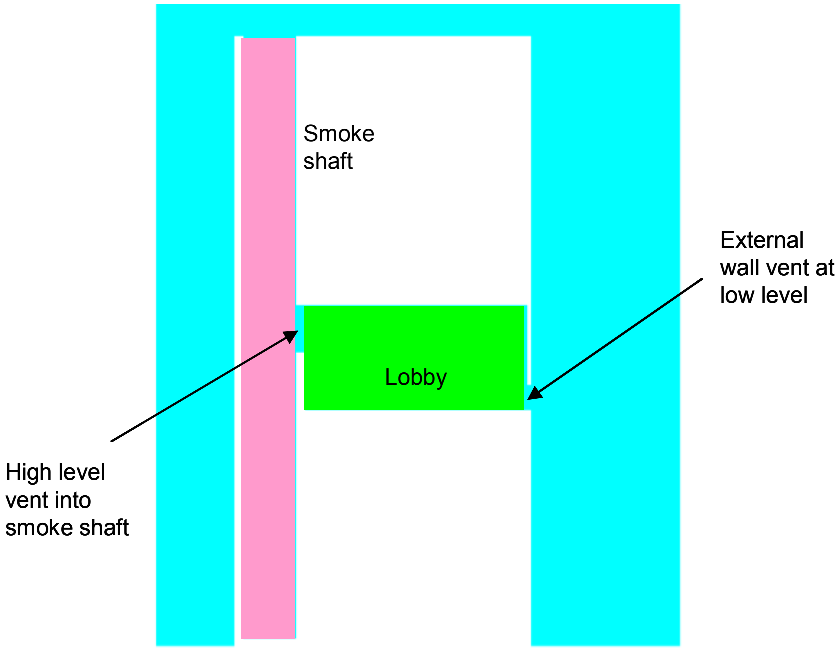


Figure C7 Illustration of a combination of a smoke shaft and a low level external wall vent.

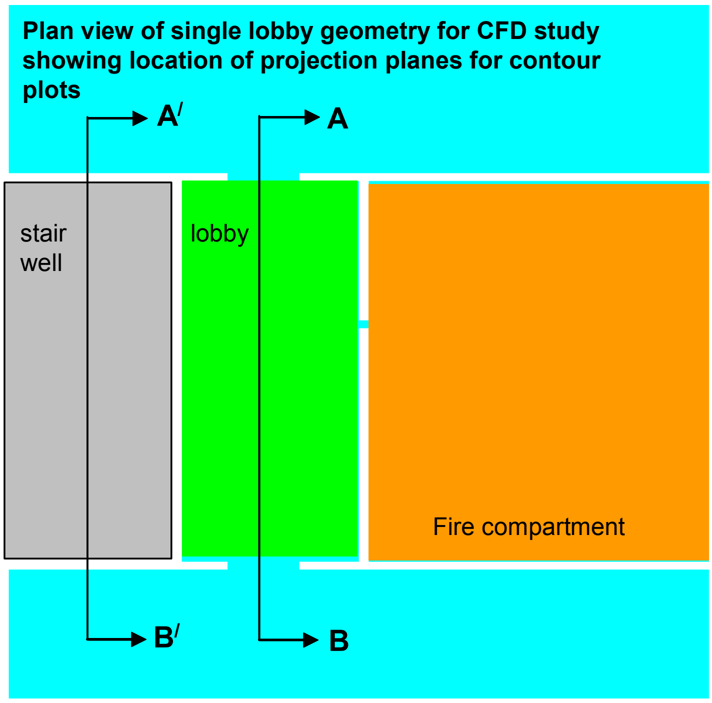


Figure C8 Location of plane for 'visibility distance' contour plots in Appendix D for single lobby geometry

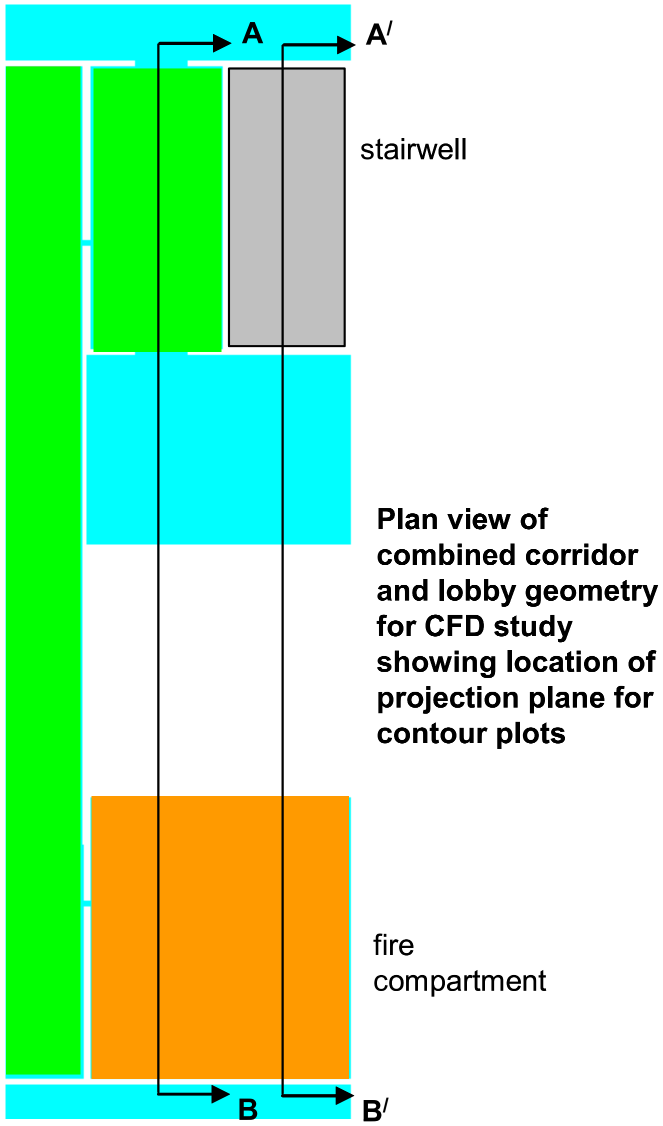


Figure C9 Location of plane for 'visibility distance' contour plots Appendix E for corridor and lobby geometry

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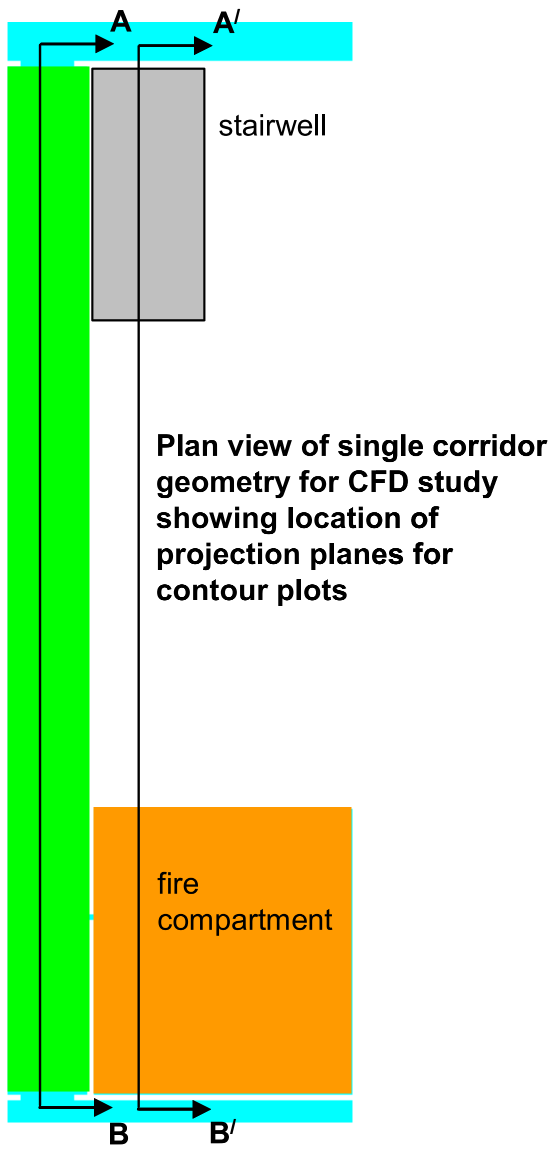

Figure C10 Location of plane for 'visibility distance' contour plots Appendix F for single corridor geometry